Temporal changes in soil temperature at Wolverhampton, UK and Hohe Warte, Vienna, Austria 1976 to 2010

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Abstract

Soil temperatures from 1976 to 2010 are reported from two sites: Compton (UK) and Hohe Warte (Austria). Soil temperature at Compton significantly increased between 1976 and 2010 by +0.04˚C to +0.08˚C $year^{-1}$, depending on depth. Temperature increases were greater in winter. Mean annual temperature at Hohe Warte increased by around 0.03˚C per year from 1976-2010. Significant temperature increases were recorded at Hohe Warte in summer, but not in winter. These differences were attributed to greater snow cover at Hohe Warte insulating the soil in winter, and to the drier summers at Hohe Warte enabling more rapid soil warming.

Keywords: soil temperature; global warming; urban heat island

Introduction

Soil temperature is determined by the available heat energy that the soil absorbs, with solar radiation being the primary source (Brady and Weil 1999). Chow *et al*. (2011) found that, in an urban environment, soil temperature is strongly correlated (R = 0.869) with the dry bulb air temperature, whereas its dependence on relative humidity, precipitation, global solar radiation or wind speed was weak (R <0.250 in all cases). Snow cover, irregular episodes of cloud cover and droughts may also influence soil temperatures. Snow cover can provide an effective insulation barrier that creates an observable lag in the thermal response of a soil relative to changing air temperature (Fullen and Smith 1983; Mackieiwicz 2012). Soil temperature fluctuates when the ratio of heat energy absorbed by soil, to energy lost from soil, changes. This is a dynamic ratio and changes over time and space. Soil temperature variation in different layers is a result of complex processes. The correlation with air temperature generally decreases with depth (Liu *et al*. 2013). Study of temperature variation in different layers of soil is useful in understanding surface energy processes and regional environmental and climatic conditions (Hu and Feng 2003).

Soil temperature has great significance for the growth and hence productivity of agricultural crops (Kaspar and Bland 1992; Wraith and Ferguson 1994; Bollero *et al*. 1996; Hu and Buyanovsky 2003) and forest plantations (Balisky and Burton 1995). Moreover, soil temperature affects plant diseases, soil hydrology and the over-wintering of pathogens (Marshall and Holmes 1979; Phillips *et al*. 1999; Pivonia *et al*. 2002). Generally, the growth and development of most annual crop plants cease at temperatures <6–10˚C (Subedi and Fullen 2009). Thus, soil temperatures below this range inhibit root growth. Soil temperatures at different soil depths between 5-60 cm at a UK research site over 35 years (1976-2010) and at a site in Austria at 10 cm over the same period are reported and discussed.

Materials and methods

The Plant and Environment Research Unit at Compton Park, Wolverhampton (UK) was used for agronomic studies on a range of crops, including Miscanthus (*Miscanthus giganteus*). The site is located three km west of Wolverhampton City centre (U52.587059N, 2.165876W;K National Grid Reference SO889989) (Figure 1). The site covered around 2.2 ha and was largely level, but with a general slope to the north. The weather station was at the western side of the area at 116 m OD.

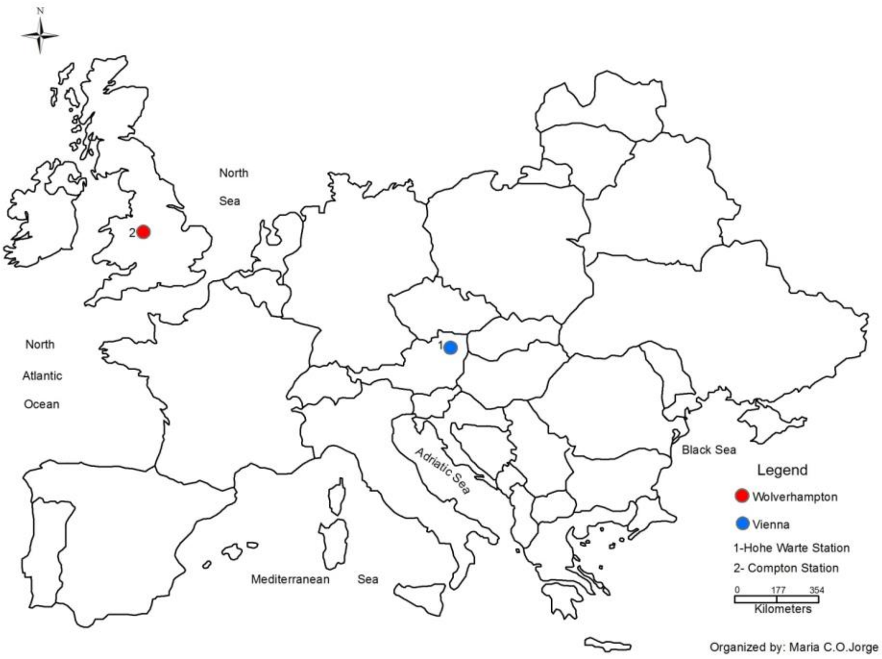

Figure 1. Location of the sites at Wolverhampton and Vienna.

Soil temperature data at Compton were taken at different soil depths under a short grass cover as part of long-term meteorological monitoring to support studies at Compton. Mercury glass thermometers (precision ±0.2˚C) were installed at depths of 5, 10, 20, 30 and 60 cm. Readings were taken daily (0900 GMT) beginning in August 1975 and ending in December 2010, other than at weekends and national holidays. In this study the data recorded from 1 January 1976 to 31 December 2010 were collated and analysed. The soil belongs to the Salwick series, which are deep reddish fine loamy soils with slowly permeable subsoils developed over reddish till and glaciofluvial drift (Ragg *et al*. 1984). The FAO/UNESCO classification is Dystric Cambisol (FAO, 1974). A typical texture is sand (2000±60 µm) 41.4%, silt (60±2 µm) 51.3% and clay (<2 µm) 7.3%; soil organic matter content 2.7% by weight) (Brandsma *et al*. 1999).

We also report soil temperature trends over the same period from a site in Austria, Hohe Warte, near Vienna. Soil temperatures and snow cover in Austria were measured at the Zentralanstalt für Meteorologie und Geodynamik (ZAMG: http://www.zamg.ac.at; accessed 28/07/16) (Central Institute for Meteorology and Geodynamics), 1190 Vienna, Austria, co-ordinates: 48.249185N, 16.355085E, altitude: 203 m (Figure 1). The soil type was carbonate-free brown soil with relict brown soils.

We compared the soil temperature trends at Compton with soil temperature trends reported for a UK rural site 11 km west of Compton at Hilton in Shropshire by Subedi and Fullen (2009). The soils at Hilton are loamy sands of the Bridgnorth series, developed over soft Triassic sandstone (Ragg *et al*. 1984) with a mean soil depth of around 70 cm. Full details of the Hilton site are provided by Subedi and Fullen (2009).

Statistical analyses (descriptive statistics, correlation and regression analysis and t-tests) were calculated using MINITAB Release 14.1. Regression analyses of temperature trends over time were carried out on the full datasets, for each month and for the annual means, and for 15-year running means to remove most of the 'noise' associated with short-term fluctuations (Brazel *et al*. 2000).

Results

General findings

Mean monthly soil temperatures at Compton ranged between 3.0˚C in January at 5 cm depth and 18.2˚C (July at 5 cm) (Table 1). Monthly temperatures showed the pattern typical of temperatures in lowland England with the coldest mean temperatures in January and February and the warmest in July and August. Mean annual temperature increased at all depths from 1976-2008 and by a mean of around 0.04˚C per year at both 5 and 60 cm (Figure 2).

Table 1.

Mean monthly and annual soil temperatures 1976-2010 at Compton, UK. Number of readings = 35. Standard deviation in brackets.

Month	5 cm	10 cm	20 cm	30 cm	60 cm	Precipitation (mm)
January	3.0 (1.47)	3.1 (1.-37)	3.6 (1.31)	3.9 (1.24)	5.2 (1.10)	58 (30.5)
February	3.2 (1.63)	3.3 (1.49)	3.7 (1.41)	4.0 (1.38)	5.0 (1.24)	43 (26.7)
March	4.9 (1.36)	4.9 (1.25)	5.2 (1.19)	5.4 (1.12)	5.9 (1.07)	49 (23.6)
April	8.5 (1.15)	7.8 (1.10)	7.9 (1.08)	8.1 (0.96)	8.3 (0.79)	55 (33.7)
May	13.0 (0.97)	11.9 (0.87)	11.7 (0.88)	11.6 (0.82)	11.2 (0.71)	57 (35.0)
June	16.4 (1.19)	15.4 (1.07)	15.1 (0.99)	14.9 (0.94)	14.0 (0.72)	64 (46.1)
July	18.2 (1.42)	17.4 (1.44)	16.9 (1.18)	16.8 (1.00)	16.0 (0.81)	60 (36.3)
August	17.2 (1.28)	16.4 (1.24)	16.4 (1.22)	16.6 (1.12)	16.5 (0.86)	63 (34.1)
September	13.8 (1.40)	13.4 (1.09)	13.8 (1.02)	14.3 (0.95)	15.1 (0.75)	55 (34.8)
October	9.9 (1.30)	9.8 (1.24)	10.4 (1.14)	11.0 (1.14)	12.4 (0.71)	71 (29.9)
November	6.2 (1.33)	6.2 (1.24)	7.0 (1.13)	7.5 (1.02)	9.3 (0.82)	63 (26.9)
December	4.0 (1.23)	4.0 (1.18)	4.5 (1.28)	5.0 (1.11)	6.8 (1.14)	67 (28.5)
Annual mean	9.8 (0.60)	9.4 (0.76)	9.6 (0.78)	9.8 (1.23)	10.5 (0.60)	705 (147.5)

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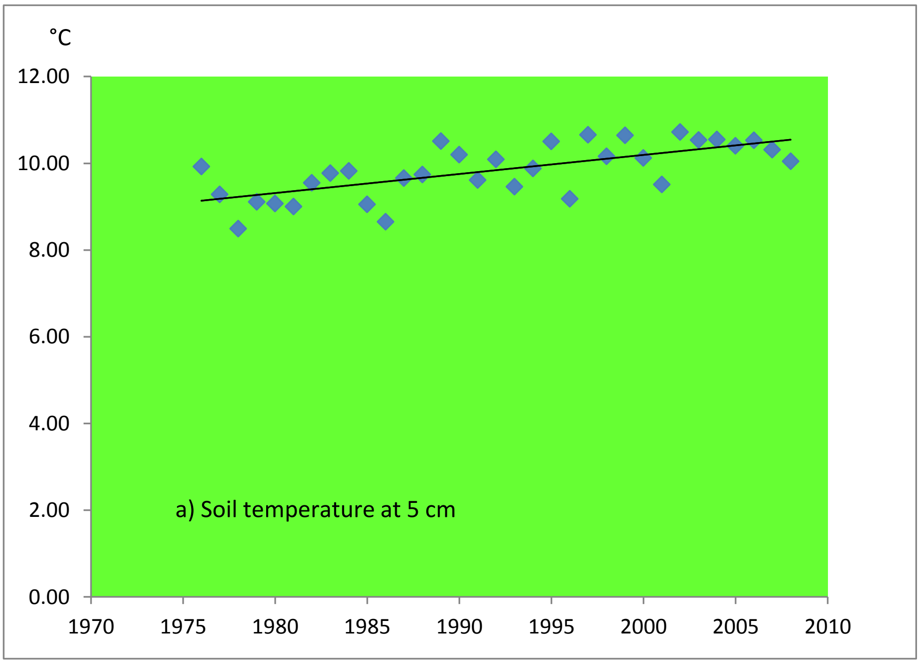


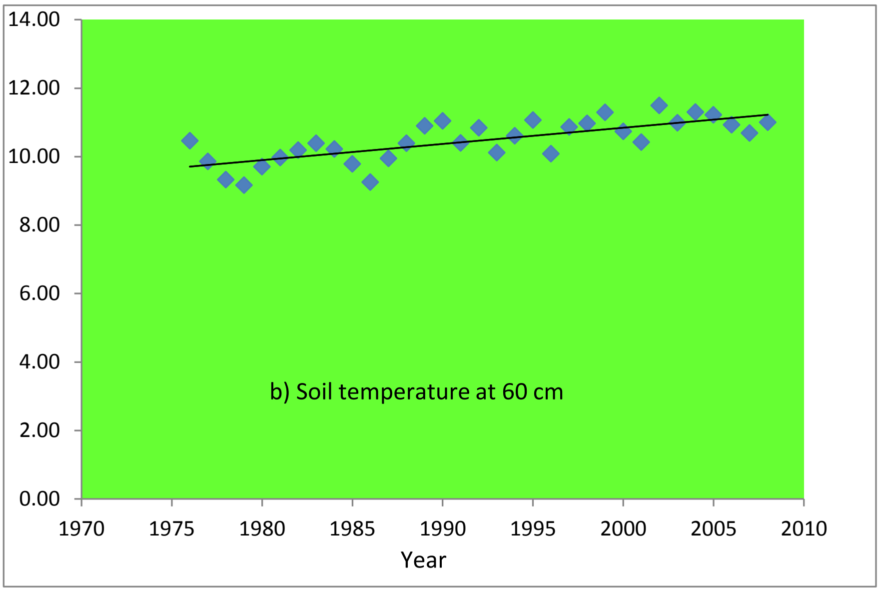


Figure 2. Mean annual soil temperatures 1976–2010 at Compton
a) at 5 cm depth
$T = 9.2 + 0.037$ Year
$\%R^2 = 38.0$
$P = <0.001$.

b) at 60 cm depth
$T = 9.7 + 0.042$ Year
$\%R^2 = 49.0$
$P = <0.001$.

Mean monthly soil temperatures at Hohe Warte ranged between 2.3˚C in January at 10 cm depth and 21.0˚C (August at 5 cm) (Table 2). Monthly temperatures showed the pattern typical of temperatures in Austria, with the coldest mean temperatures in January and February and the warmest in July and August. Mean annual temperature increased from 1976-2010 by a mean of around 0.03˚C per year at 10 cm (Figure 3).

Table 2.
Mean monthly and annual soil temperatures 1976-2010 at Vienna, Hohe Warte, Austria. Standard deviation in brackets.

Month	**10 cm**
January	2.3 (0.91)
February	2.4 (1.29)
March	4.9 (1.65)
April	9.8 (0.95)
May	15.0 (1.10)
June	19.0 (0.91)
July	20.9 (0.92)
August	21.0 (0.85)
September	17.7 (0.82)
October	13.3 (0.76)
November	8.0 (0.89)
December	3.9 (0.80)
Annual mean	11.5 (0.60)

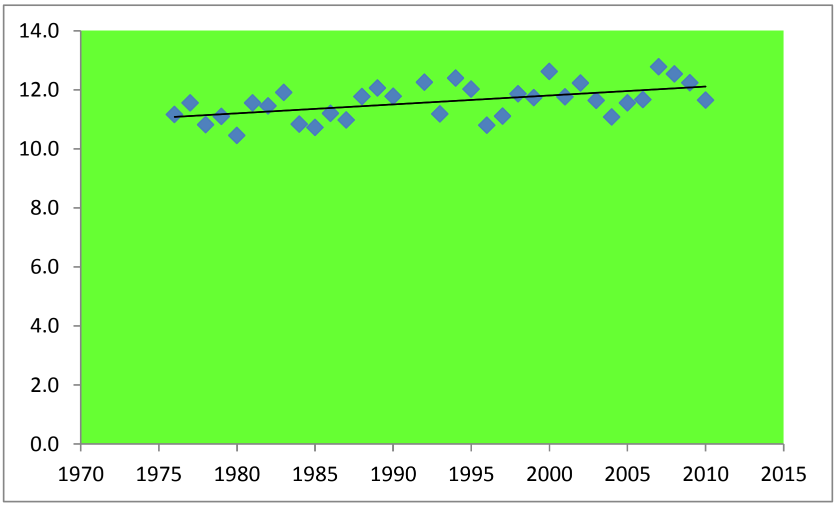


Figure 3. Mean annual soil temperatures 1976–2010 at Hohe Warte at 10 cm depth
$T = 10.9 + 0.0325$ Year
$\%R^2 = 10.1$
$P = 0.035$.

Temperature fluctuations at different soil depths at Compton

Annual mean soil temperature varied by between 2.2-2.4˚C at all soil depths during the measurement period. During winter, soil temperature increased with increasing depth (Table 1). This was because cool air and frost/snow decreased soil temperatures near the surface. However, from May-August soil temperature decreased with depth (Table 1). This is because surface soil temperature was more responsive to aerial meteorology than the subsoil, where the meteorological effects became progressively attenuated with depth.

Seasonal trends

At Compton soil temperature at 5 cm increased most in January and September (R^2 = 0.28, n = 35, p = 0.001; R^2 = 0.24, n = 35, p = 0.002, respectively; Table 3), while there were no significant increases in temperature in May, June or August. Broadly similar patterns were evident for the other soil horizons, although the months with the greatest and most significant increases in temperature varied somewhat, as did the number of summer months for which there was no increase in temperature between 1978-2010 (Table 3). At Hohe Warte, although there was a significant (p = 0.046 to 0.002) increase in annual temperature, the increase was significant for only five months. Unlike Compton, it was the summer months at Hohe Warte (July and August) when significant increases in temperature were recorded and winter months (January and February) when there were no significant changes in temperature between 1976-2010 (Table 4).

Table 3. Correlation coefficients between mean annual and mean monthly soil temperatures and time at Compton, UK. Months selected in which the greatest and smallest temporal trends were recorded. Number of observations = 35

Soil depth (cm)	**Annual or monthly mean**	**R^2**	**Probability**	**Mean annual change in temperature (˚C)**
5	Annual	0.38	<0.001	+ 0.037
	January	0.28	0.001	+ 0.082
	February	0.10	0.036	+ 0.057
	March	0.14	0.017	+ 0.053
	April	0.14	0.014	+ 0.046
	May	0.00	NS	
	June	0.00	NS	
	July	0.08	0.056	-0.045
	August	0.00	NS	
	September	0.24	0.002	+ 0.070
	October	0.10	0.035	+ 0.045
	November	0.26	0.001	+ 0.068
	December	0.07	0.073	+ 0.037
10	Annual	0.49	<0.001	+ 0.053
	January	0.26	0.001	+ 0.073
	February	0.09	0.041	+ 0.050
	March	0.08	0.058	+ 0.040

	April	0.26	0.001	+ 0.052
	May	0.02	NS	
	June	0.00	NS	
	July	0.00	NS	
	August	0.00	NS	
	September	0.37	<0.001	+ 0.067
	October	0.17	0.007	+ 0.054
	November	0.25	0.001	+ 0.063
	December	0.05	NS	
20	Annual	0.57	<0.001	+ 0.058
	January	0.24	0.002	+ 0.067
	February	0.11	0.027	+ 0.051
	March	0.10	0.038	+ 0.041
	April	0.38	<0.001	+ 0.068
	May	0.21	0.004	+ 0.043
	June	0.06	0.084	+ 0.031
	July	0.00	NS	
	August	0.04	NS	
	September	0.42	<0.001	+ 0.066
	October	0.25	0.001	+ 0.058
	November	0.27	0.001	+ 0.059
	December	0.10	0.037	+ 0.044
30	Annual	0.37	<0.001	+ 0.075
	January	0.18	0.008	+ 0.057
	February	0.10	0.042	+ 0.047
	March	0.07	0.074	+ 0.034
	April	0.33	<0.001	+ 0.056
	May	0.22	0.003	+ 0.040
	June	0.17	0.010	+ 0.042
	July	*	*	*
	August	*	*	*
	September	*	*	*
	October	0.10	0.035	+ 0.040
	November	0.22	0.003	+ 0.049
	December	1.3	NS	+ 0.022
60	Annual	0.49	<0.001	+ 0.042
	January	0.21	0.004	+ 0.053
	February	0.18	0.007	+ 0.054
	March	0.12	0.025	+ 0.040
	April	0.38	<0.001	+ 0.048
	May	0.34	<0.001	+ 0.041
	June	0.07	0.074	+ 0.022
	July	0.00	NS	
	August	0.04	NS	
	September	0.38	<0.001	+ 0.048
	October	0.32	<0.001	+ 0.041
	November	0.33	<0.001	+ 0.047
	December	0.16	0.011	+ 0.049

NS = Not significant (P >0.05).

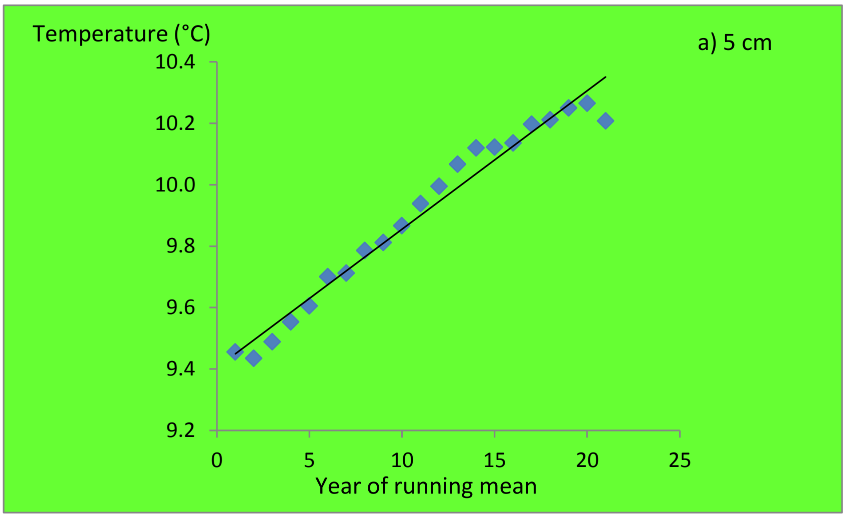
Table 4. Correlation coefficients between mean annual and mean monthly soil temperatures and time at Hohe Warte, Austria. Months selected in which the greatest and smallest temporal trends were recorded. Number of observations = 35

Soil depth (cm)	**Annual or monthly mean**	**R^2 %**	**Probability**	**Mean annual change in temperature (˚C)**
Hohe Warte				
10	Annual	10.1	0.035	+0.033
	January	0.0	NS	NA
	February	4.6	NS	NA
	March	0.0	NS	NA
	April	8.8	0.046	+0.045
	May	5.0	NS	NA
	June	0.0	NS	NA
	July	9.1	0.046	+0.037
	August	11.4	0.027	+0.042
	September	0.0	NS	NA
	October	0.0	NS	NA
	November	23.6	0.002	+0.014
	December	5.7	0.092	+0.030

Preliminary evidence of increasing soil temperature

At Compton there was a trend of increasing soil temperature at all depths. R^2 ranged from 0.37 at 30 cm (n = 35) to 0.57 at 20 cm (n = 35), and P was <0.001 at all depths (Table 2 and Figure 2). The mean annual increase in temperature ranged from 0.04˚C at 5 and 60 cm to 0.08˚C at 30 cm. Comparison of soil temperature at 5 cm over the measurement period (1976 and 2010) revealed that the mean annual temperature increased by 1.3˚C at 5 cm depth and 2.6˚C at 60 cm (Table 3 and Figure 3).

Assessing trends using running means greatly increased the R^2 coefficients: from R^2 = 0.38 to 0.97 at 5 cm and R^2 =0.49 to 0.97 at 60 cm (Figure 4). This trend, to increase R^2 to ≤0.95, was also observed at the other depths (10, 20 and 30 cm). When the Hohe Warte results were expressed as running means R^2 increased to 0.90 (Figure 5).



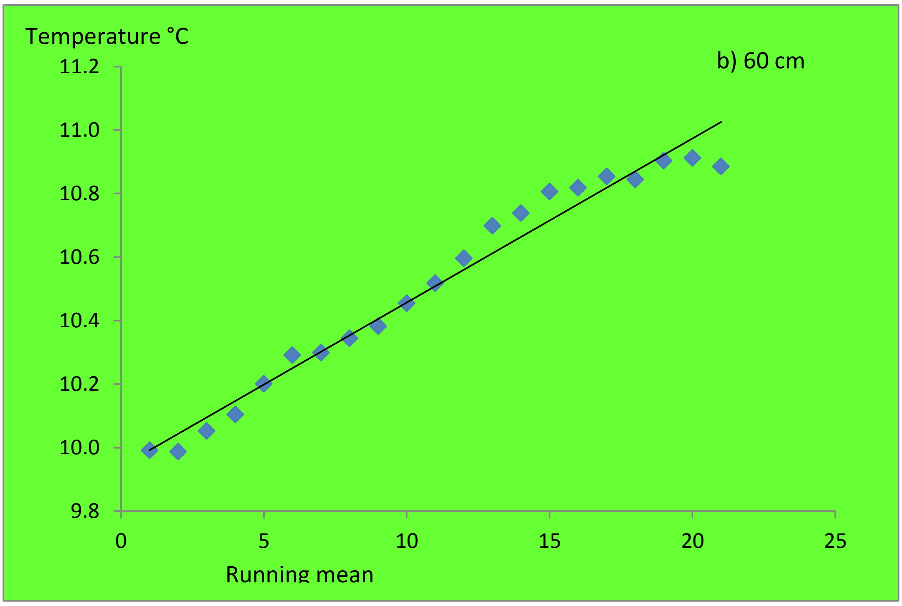


Figure 4. 15-year running mean annual soil temperatures 1976–2010 at Compton
a) at 5 cm depth
$T = 9.40 + 0.045$ Year
$\%R^2 = 96.7$
$P < 0.0001$

b) at 60 cm depth
$T = 9.94 + 0.0516$ Year
$\%R^2 = 97.0$
$P < 0.0001$.

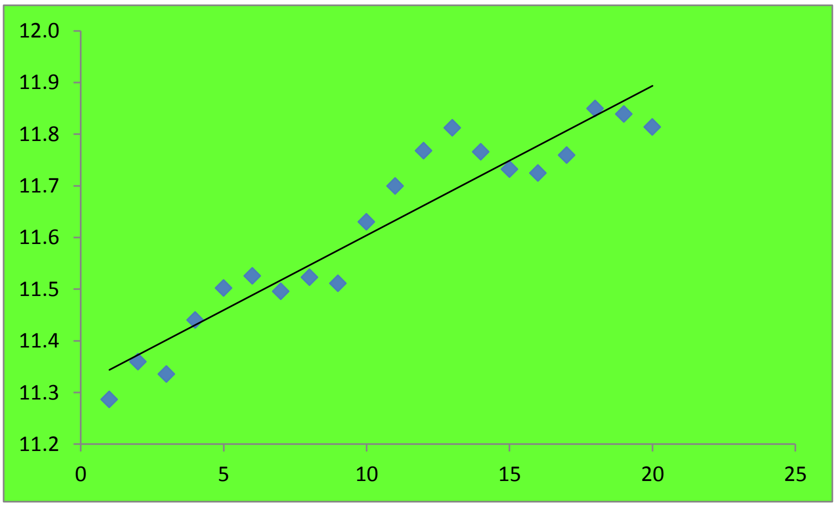


Figure 5. 15-year running mean annual soil temperatures 1976–2010 at Hohe Warte at 10 cm depth

T = 11.30 + 0.029 Year
%R^2 = 89.5
P <0.0001.

Discussion

Differences in trends between Compton and Hohe Warte

Although mean monthly temperatures for November and December increased at Hohe Warte, as for Compton, there was no increase in mean monthly temperatures in January or February at Hohe Warte, in contrast to the findings at Compton. We suggest this difference may be due to snow cover insulating the soil at Hohe Warte in those months, as suggested by the findings of Mackieiwicz (2012) and supported by ZAMG data on snow cover. There were few days of snow cover over the period in which soil temperature measurements were made at the UK site.

Another contrast is the increase in temperature at Hohe Warte in July and August, when there were no significant temperature increases in the summer months at Compton. We suggest this difference may have arisen due to the greater summer temperatures at Hohe Warte leading to drier soils and hence a reduced thermal capacity.

Hohe Warte belongs to the Pannonian climate, which is typical for East Austria. The Pannonian climate can be found in moderate continental climatic zones and is characterised by warm and dry summers. Winters are cold, but also dry with little snow fall. However, snow cover may persist for longer due to the consistently cold temperatures during winter: https://de.wikipedia.org/wiki/Pannonisches_Klima (accessed 28/07/16). This contrasts with the UK, where snow usually melts within a few days or even hours after falling.

Comparison of the Compton results with results from the nearby UK rural site at Hilton

The mean annual increase in soil temperature at 5 cm depth at Compton (0.04˚C) was less than that reported from the nearby UK site at Hilton (0.08˚C). At Compton the increase in soil temperature did not show any trend with depth, whereas at Hilton the increases in soil temperature decreased with increasing depth (Subedi and Fullen, 2009). Based on the particle size distribution reported above, the soil at Compton is classified as a silt loam (ZL) according to the soil texture classification published by Natural England (2008) and thus heavier in texture than the loamy sand (LS) at Hilton (Subedi and Fullen, 2009) and therefore the Compton soil will be slower to warm or cool. This difference in texture may explain the buffered response at Compton. In common with the findings at Hilton, temperatures at Compton increased less in the summer months than in other months (Table 2).

Is the warming at Compton due to the urban 'heat island' effect?

Since the Compton site is within an urban area, soil temperatures might be expected to be greater than at nearby rural sites. However, mean annual soil temperatures at Compton were similar to those measured at Hilton ranging from 9.4˚C (10 cm depth) to 10.5˚C, compared with the range of 9.5˚C (20 cm depth) to 10.7˚C (10.7 cm depth) reported for Hilton (Subedi and Fullen 2009). As noted above, the increase in temperature at Compton over the measurement period was somewhat less than that at Hilton.

Brazel *et al*. (2000) compared air temperature measurements between urban and nearby rural sites and measured maximum differences in Tmin of 4-5˚C and 1.7˚C in Tmax. Brazel *et al*. (2000) confirmed earlier work which correlated increasing differences between urban and rural temperatures with increasing urban populations, noting that as the population of Baltimore stabilised and then decreased there were no further increases in temperature differences with nearby rural areas. Details of the population of Wolverhampton are unavailable for the precise period of temperature measurement at Compton. However, information from the decadal census of 1971-2011 inclusive indicates there was little change in the population over the measurement period, which decreased from 269,166 in 1971 to 236,573 in 2001 and increased to 249,470 in 2011. In addition, the Compton location is very much suburban, at the urban fringe, and not therefore subject to the greatest heat island effect. Hence, soil warming at Compton between 1976-2010 is unlikely to be due to the urban heat island effect.

It is possible the greater average annual increase in temperature was greater at Hilton due to the lighter soil texture (LS versus ZL) retaining less water and therefore requiring less heat input to raise temperature than at Compton. This suggestion is consistent with our explanation of the reason for the greater summer temperature increase at Hohe Warte.

Conclusions

Soil temperatures at 5 cm at Compton increased at a rate of around 0.04˚C year^{-1} between 1976-2010. Soil at 60 cm warmed at a similar rate. Increased soil temperatures were generally greater in winter, which supports evidence that winters are tending to become warmer. Although the trends in warming were similar at Compton (UK) and Hohe Warte (Vienna, Austria), the average annual increase was less marked at the latter, possibly due to the insulating effects of winter snow cover. The measured increases in soil temperature at Compton were less than those reported from the nearby UK rural site at Hilton. This, together with the relatively static population of the Wolverhampton urban area, mean that the increases in soil temperature are unlikely to be due to the urban heat island effect. Hence the measured warming appears to be a result of a changing climate. The difference in average annual warming between Compton and Hilton provides indirect evidence of possible effects of soil texture on soil temperature.

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